Leadership in Sustainable Infrastructure

Leadership en Infrastructures Durables

Vancouver, Canada

May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

A REVIEW OF HISTORICAL EXTREME WIND SPEEDS IN A CHANGING CLIMATE AT SOME MAJOR CANADIAN CITIES

Li, Sihan[1,2], Irwin, Peter[1], Kilpatrick, John[1], Gibbons, Mike[1], Sifton Valerie[1]

[1] Rowan Williams Davies and Irwin Inc. (RWDI), Canada

[2] sihan.li@rwdi.com

Abstract: Some efforts have been made to consider the probable impacts of climate change on design wind speeds in tropical cyclone prone regions, such as Australia and the east coastal line of the United States. However, in Canada, the extreme wind speeds are mostly dominated by non-hurricane wind events. One recent study based on historical ground observations and re-analysis data indicates that stations over the Gulf of St. Lawrence of Canada mostly have no clear trend in terms of annual maximum wind speeds, but increasing variability was identified. A similar study shows that the historical monthly mean wind speed for the same region is decreasing. A recent study applies several weather forecast models for some possible future climate scenarios at various sites in Ontario, indicating an increase in the frequency of gust wind speeds between 28 km/h and 70 km/h. These studies point to three main tasks that need more research: obtaining a better understanding of any possible trends in historical data; the use of finer spatial scale regional climate model to predict future climate scenarios; and the development of more appropriate downscaling methods to relate the relationship between upper level and ground level wind speeds. The first task is critical to setting up the basis for measuring the quality of future climate modeling and to better understand how the current wind climate may translate to a probable future wind climate. From this perspective, this study explores the historical wind speed data in a number of major Canadian cities. Historical extreme wind observations are investigated in terms of the frequency of extreme wind events, seasonality and directionality. The probable impact on design wind speeds is discussed.

1 INTRODUCTION

Wind load is one of the most important parameters for building design, especially for high rise buildings. The design wind velocity is conventionally estimated from ground observations. Numerical simulation sometimes can be employed to extend the sample database used to evaluate the return period wind speed when the ground observations are insufficient, such as records for hurricane wind speeds (Vickery et al. 2009, Li and Hong 2014 & 2016). In Canada, the design wind speeds are dominated by extra-tropical wind storms or some local phenomena such as thunderstorms. The long term ground observations of wind speeds are typically used to estimate the return period wind speed and map the wind hazard for Canada (e.g. Hong et al. 2014). With increasing concern for the impact of a changing climate on infrastructure, some studies have applied numerical forecast models to predict the change of wind speed in future warmer climate scenarios. Among these studies, Cheng et al. (2013) indicate that in a warmer future climate, the frequency of gust wind speeds over some specific threshold values, such as 90 km/h, are most likely to increase for most regions of Canada. This gust wind speed is associated with a sudden, rapid and brief increase in wind speed. Conservatively, the corresponding hourly mean wind speed for this 90 km/h gust wind speed is no more than 54 km/h. This speed is less than the lowest value of design wind pressure velocity for 10-year (68.4 km/h) and 50-year (77.4 km/h) return period in the National Building Code of Canada (NBCC) 2015. The study of Cheng et al. (2013) indicates that for gust wind speeds greater than 90 km/h, the annual mean frequency of these speeds will increase in a future warmer climate. This may indicate that the frequency of wind speeds in the design speed range will increase as well. By definition, the return period wind speed is related to the probability of exceedance (occurrence of event over specific value). The change of annual occurrence of extreme wind speeds may have an impact on the estimated return period wind speeds. To deal with this changing occurrence rate of the extreme wind speeds, non-stationary probabilistic model needs to be employed. A non-stationary probabilistic model can be applied by assuming the probabilistic distribution parameters are varying with time. To fit such a non-stationary model, besides knowing the potential future change of the occurrence of extreme wind events, one has to know its historical characteristics as well. To the author's best knowledge, there are few studies publically available that investigate historical trends of the occurrence of extreme wind events. To better appreciate the historical characteristics of extreme wind events under a changing climate, one of the tasks in this study is to investigate trends in the occurrence rate of extreme wind events.

Besides the occurrence rate of the extreme wind speeds, the change in magnitude of the extreme wind speeds also has a direct impact on the estimated return period wind speeds. There are some studies exploring the trends of the historical wind speed data, such as Tuller (2004) and Wan et al. (2009). In these studies, the historical trend of long term (monthly in Wan et al. (2009) and annual in Tuller 2004) mean wind speeds is investigated. Tuller (2004) finds that four stations in west Canada have a decreasing trend for the annual mean wind speed, which is consistent with conclusions drawn by Wan et al. (2009). Broadly speaking, this decreasing trend identified by Wan et al. (2009) covers most of the south part of Canada, while only regions in the far North and east coast close to the Gulf of St. Lawrence have an increasing trend. A similar study by Hundecha et al. (2008) of the Gulf of St. Lawrence, using annual maximum wind speeds, found an increasing trend in part of the region, but a decreasing trend in the north part of this region. These studies generally agree that a decreasing trend appears in the long term mean wind speed for many meteorology stations of Canada. Only some limited effort was made to investigate the trend of extreme wind speeds, which are key to estimating design values. Due to the large uncertainty of current numerical weather forecast models, it is hard to reliably quantify the changes on annual maximum extreme wind speeds. Trends in the historical annual maximum wind speeds can be investigated as a basis for predicting future changes by assuming the same trends continue in future. This idea is one of the most popular approaches when non-stationary probabilistic models are employed to predict the percentile value of the extreme events in a future period (such as in Hundecha et al. 2008). The objective of this study is to conduct a trend analysis for the extreme wind speeds, which include the maximum wind speeds for an entire year, and for the summer, winter, and other seasons. The annual directional maximum wind speeds are considered as well in this study because the wind directionality often could be a key parameter for building design.

2 DATA AND STANDARDIZATION

This study uses meteorology stations at 20 cities across Canada. The geographical location and range of data used in this study are provided in Figure 1. It can be seen from Figure 1 that the selected stations are located in different regions across Canada, but are mostly located to the south. Note that the data for Niagara Falls is taken from the Niagara Falls International Airport on the US side of the border. Some of the data was removed in this study because of the bad data quality, such as insufficient data in a year, improper anemometer location (such as anemometer on building roof) etc. The data range used in this study for each station is listed in Table 1. Each station has more than 30 years of data. The data was standardized by conducting height corrections and exposure corrections. The height correction was conducted to convert the wind speed to standard 10m height by using the available anemometer height information provided for the meteorology station. For the exposure correction, the ESDU (2006) approach was adopted to consider the terrain change within tens of kilometers surrounding the site. The above processes are believed to homogenize the data reasonably well to standard height and terrain conditions. There might be some other factors, such as the change of anemometer type or human operation, which may also introduce some inhomogeneity into the data. These factors could not be accounted in this study due to lack of documentation and less knowledge on their impact. The statistics of the annual maximum wind speeds under stationarity assumptions, including mean value (m_{Va}), maximum value ($V_{a,max}$) and coefficient of variation (COV) of the annual maximum wind speeds, are summarized in Table 1. The return period wind speeds corresponding to design wind pressures for 50-year (V_{50}) return period given in NBCC 2015 are listed in Table 1 as well. For conversion of the design wind pressure to wind speed, the air density of 1.2929 kg/m^3 is used, consistent with the value assumed for the NBCC. It is believed that the length of records is also sufficient to carry out a trend analysis. From Table 1, it can be seen that some of the maximum values of annual maximum wind speeds are close to those 50-year return period wind speeds in NBCC. This is expected because by definition the 50-year return period wind speeds should be expected to be exceeded once in 50 years on average.

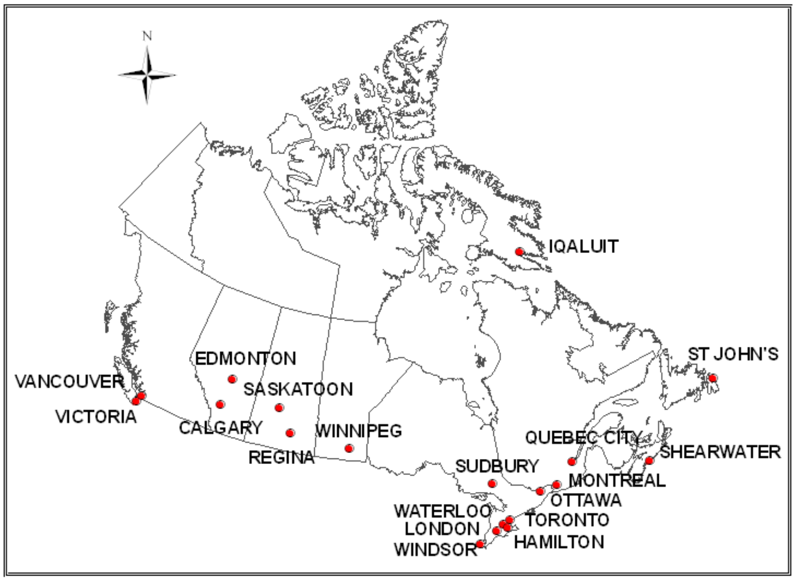

Figure 1: Geographic distribution of the meteorological station

Table 1: Statistics of the annual maximum wind speeds assuming stationarity for studied stations and their corresponding design wind speed.

City	Number of Years	m_{Va} (km/h)	$V_{a,max}$ (km/h)	COV	V_{50} in NBCC 2015 (km/h)
Calgary	30	75	94	0.11	98
Edmonton	43	65	83	0.09	95
Shearwater (Halifax)	34	70	96	0.14	108
Hamilton	46	74	98	0.11	96
Iqaluit	45	80	121	0.19	108
London	50	70	98	0.14	97
Montreal	52	69	86	0.12	92
Niagara Falls	44	72	94	0.12	93
Ottawa	55	64	83	0.13	91
Quebec	47	68	85	0.12	91
Regina	48	72	87	0.09	99
Saskatoon	46	66	95	0.15	93
St. John's	37	90	107	0.09	103
Sudbury	48	67	97	0.15	96
Toronto	53	75	91	0.09	94
Vancouver	54	62	87	0.14	98
Victoria	52	56	73	0.14	92
Waterloo	49	69	86	0.10	86
Windsor	48	74	99	0.12	97
Winnipeg	45	67	86	0.09	95

Although the data at the upper tail of the extreme value distribution has a direct impact on the estimated return period wind speed, the data at the lower tail also has an impact on the estimation of the slope parameter of the distribution. Therefore, the smaller values of annual maximum wind speed need to be considered as well. This perspective leads to the selection of threshold value for occurrence rate trend analysis in next section.

3 TREND ANALYSIS FOR EXTREME WIND SPEEDS

There are two major contributors to the return period wind speeds in a stationary climate. The first one is the magnitude of the extreme wind speeds and the other is the occurrence rate. A simple approach of estimating the return period wind speed under a stationary assumption is using the annual maximum wind speed. In this case the annual occurrence rate of the annual maximum extreme wind speeds is explicitly defined to be 1. Other probabilistic models or statistical approaches are available to estimate the return period wind speeds, such as the independent storm approach (Cook and Harris 2003, Harris 2009), peak over threshold method (POT, Simu and Heckert 1996) and a more general Poisson distribution method. Changes in the occurrence of extreme wind speeds due to non-stationary effects will have direct and explicit impacts on these methods. Therefore, in this study, a trend analysis was carried out for both annual maximum wind speeds and the occurrence rate of extreme wind speeds over a specific threshold value. A threshold wind speed of 55 km/h was selected for all studied stations. A more robust threshold wind speeds could be selected based on the 50-year return period wind speed or some percentile value of the annual maximum wind speed. However, the reason for applying this threshold wind speed is that a) this value is close to a lower percentile value of the annual maximum wind speed for each station; and b) by selecting other threshold wind speeds (+/-10 km/h), the results from the trend analysis for each station do not change.

For carrying out trend analyses, two methods are applied in this study. The first is to carry out a t-test for the best linear fit of the variable (annual maximum wind speeds or annual occurrence rate) as a function of time (i.e. number of years from start of the record). The null hypothesis is that the slope of the best linear fit is zero. If this hypothesis can be rejected, then the detected trend is considered to be statistically significant. Assuming the analyzed variable, Y, can be expressed as a linear function of time (T), Y = aT +b. The t-score for this test can be calculated by,

$$[1]\quad t_{score} = \hat{a} / \left(\sqrt{\left(\sum_{i=1}^{N} \left(y_i - \left(\hat{a} x_i + \hat{b} \right) \right)^2 \right) / (n-2)} \Big/ \sqrt{\sum_{i=1}^{N} \left(x_i - \bar{x} \right)^2} \right)$$

where, $\hat{a}$ and $\hat{b}$ are the estimated slope and intercept, x_i = time of observation from start of data, y_i = observation variable (wind speed or occurrence rate), and n = number of observations.

The analysis was assumed to indicate a statistically significant trend when the absolute value of t_{score} is less than 0.05 (i.e., 5% significance level). Yue and Pilon (2004) suggest that the Mann-Kendall Tau trend analysis can be more effective in cases where the variable is non-normally distributed, which is the case for the annual maximum wind speed that typically can be fitted into a Gumbel distribution. Therefore, to further confirm the detected trend, if there is any, the Mann-Kendall trend analysis was also carried out for all studied stations. For the variables, X, ordered by time, such as the sequential annual maximum wind speed or occurrence rate of extreme storm event per year, the Mann-Kendall S score can be defined as,

$$[2]\quad S = \sum_{i<j} \mathrm{sgn}\left(X_j - X_i \right)$$

where *sng*(•) is the sign function.

The S score is asymptotically normal with zero mean and variance of $\sigma^2 = n(n-a)(2n+5)/18$. Again a 5% significance level was used to determine the null hypothesis.

As mentioned at the beginning of this section, two major variables, including annual maximum wind speeds and occurrence rate of specific extreme wind events, were used to carry out the trend analysis. These two major variables can be further classified by,

A1) annual maximum wind speeds of mixed wind climate;
A2) annual maximum wind speeds of synoptic (non-thunderstorm) wind climate;
A3) annual maximum wind speeds of thunderstorm only wind climate;
A4) annual maximum wind speeds of seasonal wind climate;
A5) annual maximum directional wind speeds (45-degree each bin);
A6) annual occurrence of hourly mean wind speeds exceeding specific threshold value (55 km/h);
A7) annual occurrence of thunderstorm.

Table 2: Summary of trend analysis for the annual maximum wind speed for studied stations

Station Name	A1	A2	A3	A6	A7
Calgary	Decreasing	Decreasing	-	-	-
Edmonton	Decreasing	Decreasing	-	-	-
Shearwater (Halifax)	Decreasing	Decreasing	Decreasing	Decreasing	-
Hamilton	-	-	-	-	Increasing
Iqaluit	Increasing	Increasing	N/A	Increasing	N/A
London	-	-	-	-	-
Montreal	-	-	N/A	N/A	-
Niagara Falls	-	-	-	-	-
Ottawa	Decreasing	Decreasing	-	Decreasing	-
Quebec City	-	-	Decreasing	Increasing	Decreasing
Regina	-	-	-	-	-
Saskatoon	-	-	-	-	-
St. John's	-	-	N/A	Decreasing	-
Sudbury	Decreasing	Decreasing	Decreasing	Decreasing	-
Toronto	-	-	-	-	-
Vancouver	Increasing	Increasing	N/A	Increasing	N/A
Victoria	-	-	N/A	-	N/A
Waterloo	-	-	-	Increasing	-
Windsor	Decreasing	-	-	Decreasing	Decreasing
Winnipeg	-	-	-	-	Decreasing

Note: “-” denotes no statistically significant trends was detected, N/A denotes insufficient data to carry out trend analysis.

For a visual illustration, the best linear fits for the standardized annual maximum wind speeds for each studied station are plotted in Figure 2. The estimated slope and the calculated probability based on t-score are also given in each plot. For detection of the trend for annual maximum wind speeds, the Mann-Kendall trend analysis is more sensitive. Therefore, if the t-test indicated no trend but the Mann-Kendall test accepted trending, then the trend was accepted. For trend analysis for occurrence, when both tests reject the null hypothesis, the trend is confirmed. The results of the above trend analysis for tasks A1, A2, A3, A6 and A7 are listed in Table 2 for all studied stations. It can be seen from the Figure 2 and Table 2 that, for annual maximum wind speeds extracted from the mixed wind climate (A1), six of twenty stations are detected as having a decreasing trend, while only two stations are detected as having an increasing trend. The remaining 12 stations have no statistically significant trend. For stations that are detected having a trend for annual maximum wind speeds from the mixed wind climate, their synoptic annual maximum wind speeds (A2) have the same trend, except for Windsor, whose synoptic wind has no trend. There are three stations, Shearwater, Quebec City and Sudbury, which have a decreasing trend for thunderstorm extreme wind speeds (A3). Four stations were detected as having trend in the annual occurrence rate of thunderstorms (A7). These include Hamilton having increasing trend, while Quebec City, Windsor and Winnipeg having decreasing trend. The trend of annual occurrence for peak wind speed of independent storms exceeding 55 km/h (A6) for each station is generally similar to the analysis for case A1, except for Calgary and Edmonton detected as having no trend and Waterloo and Quebec City having an increasing trend, while St. John’s having a decreasing trend.

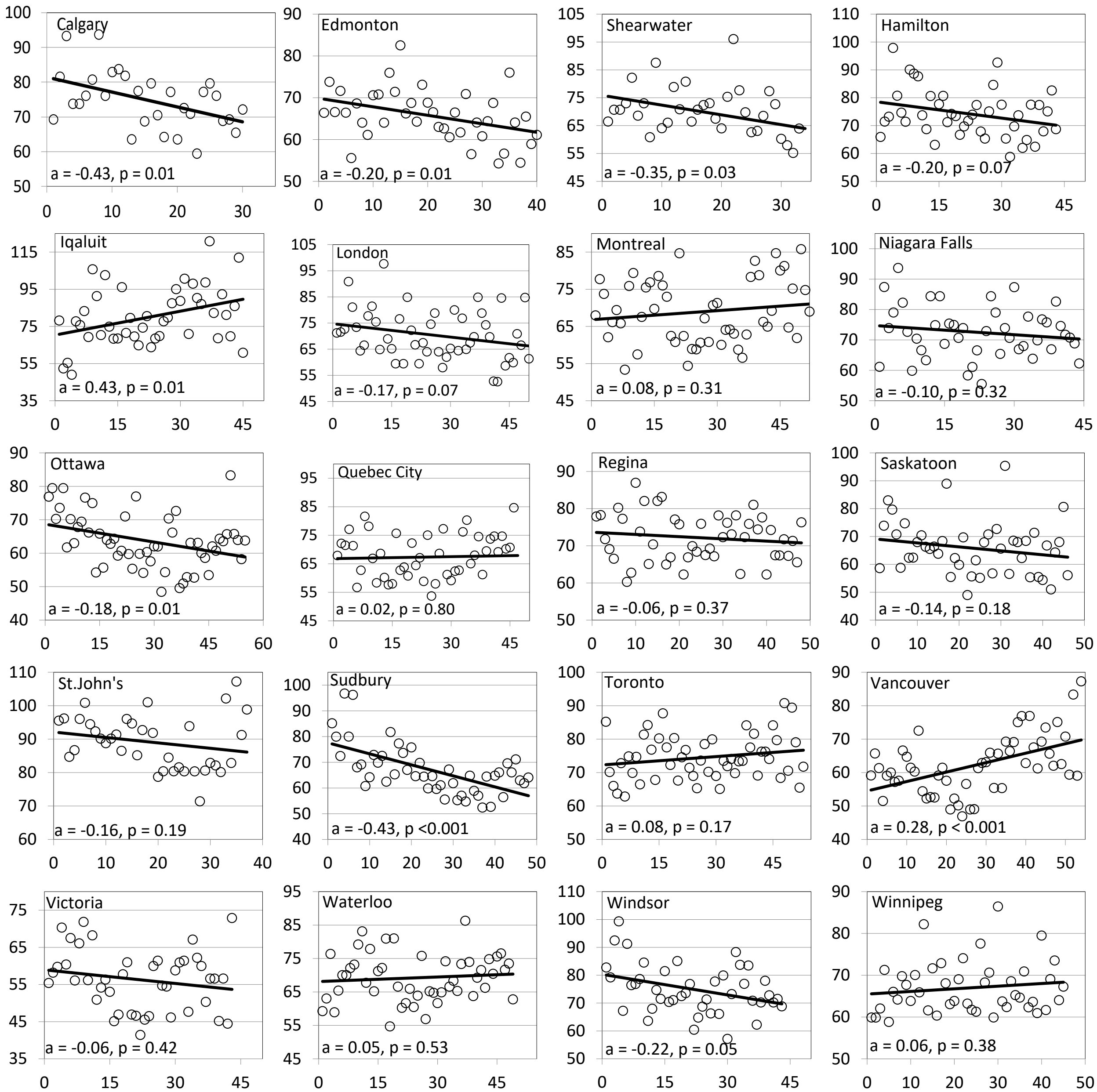

Figure 2: Trend analysis of annual maximum wind speed for each station applying T-test. X- axis represents time (year) from the start of the data and Y-axis represents the annual maximum wind speeds (km/h).

To carry out the trend analysis for seasonal extreme wind speeds, the data is first categorized based on recording time. The ranges of four seasons in this study are defined as, Spring being from March to May, Summer being from June to August, Autumn being from September to November, and Winter being from December to February of the following year. The frequencies of wind speed greater than 55 km/h for each season for each studied station are shown in Figure 3. It can be seen that for most stations, the extreme wind speeds (> 55 km/h) more frequently occur in winter or spring. The trend analysis is only carried out for the annual maximum wind speeds for each season. The results are illustrated in Figure 3 by showing a downwards arrow if there is a statistically significant decreasing trend, or an upwards arrow if an increasing trend was detected. Otherwise, no arrows are provided.

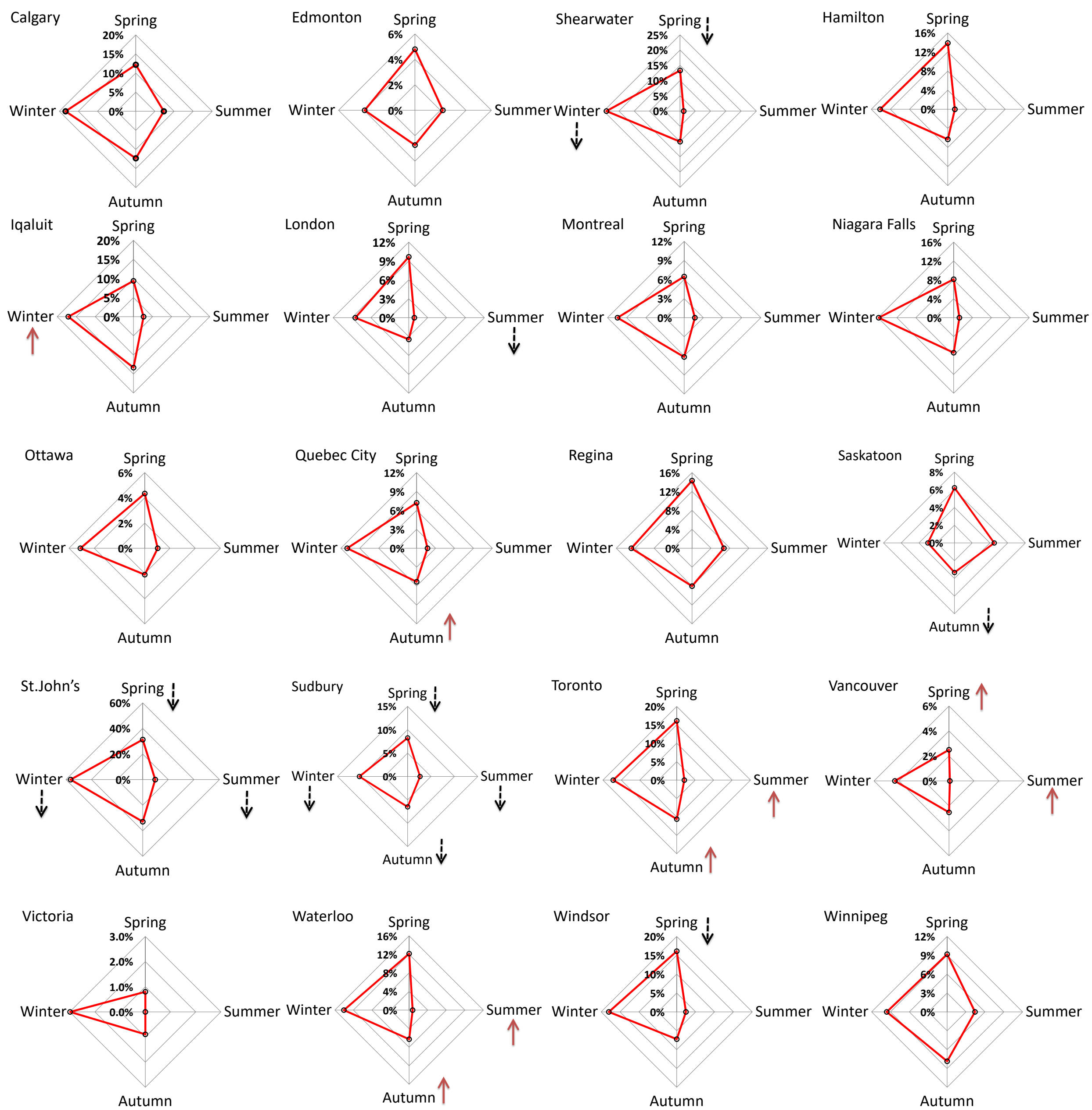

Figure 3: Trend analysis for seasonal extreme wind speeds for each studied station (upwards arrow denotes increasing trend and downwards arrow denotes decreasing trend)

It can be seen that the detected trends for the annual maximum wind speed in each season are not always consistent with the detected trend in the annual maximum wind speeds. For example, Calgary, Edmonton and Ottawa show no trends for the yearly maximum of seasonal wind speeds. However, their corresponding annual maximum wind speeds are detected as having trend. This may be because of the change of extreme wind climate is not concentrated in one season. Some of the detected trends support the trend analysis shown in Figure 2. Taking Shearwater station as an example, the winter and spring annual maximum value of seasonal extreme wind speeds are detected as having decreasing trends. The extreme wind speeds most frequently occur in winter and a bit lesser in spring. While extreme wind speeds in both seasons have a decreasing trend, the annual maximum wind speed for Shearwater station has a decreasing trend as well.

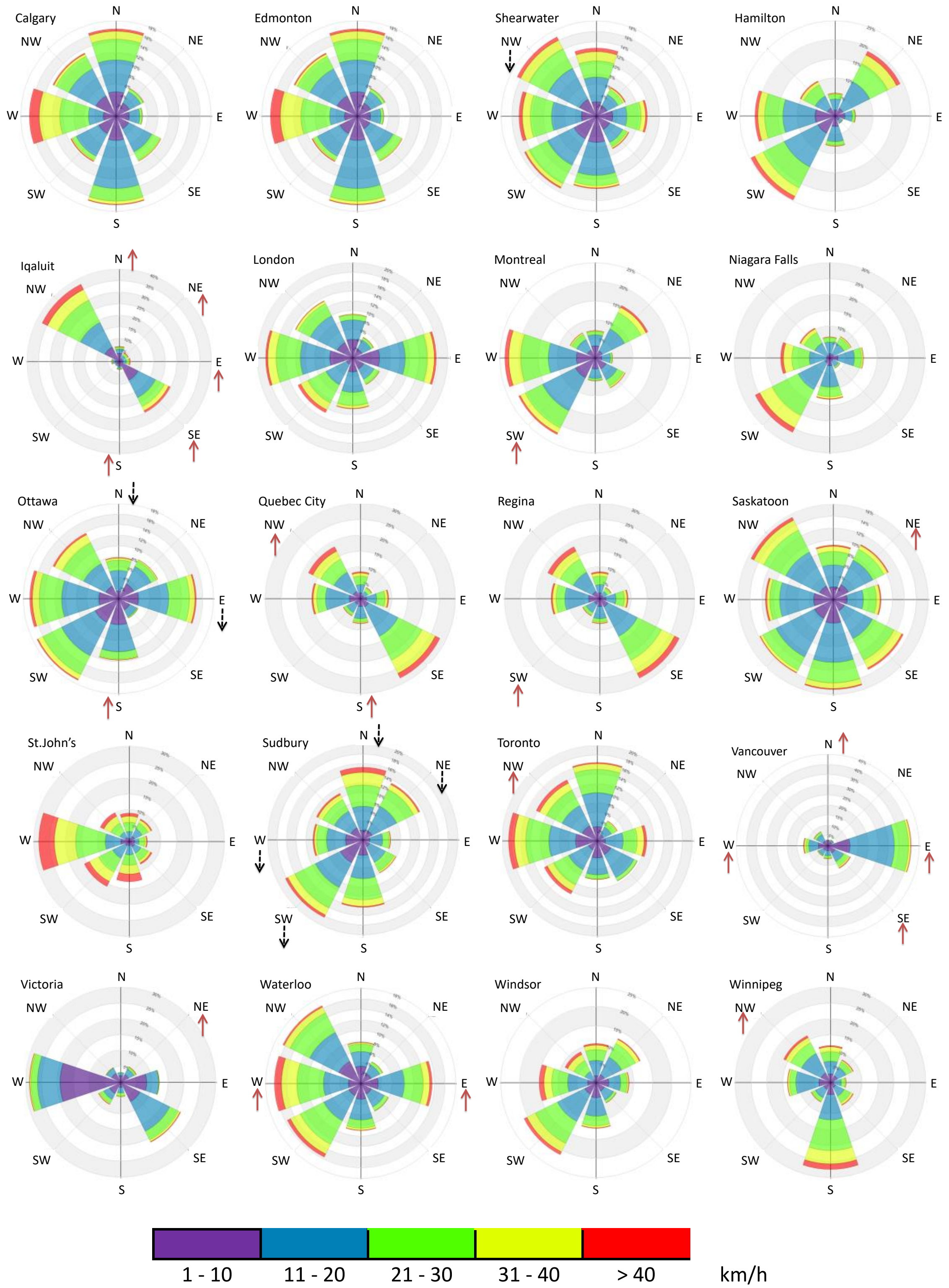

Figure 4: Trend analysis for directional extreme wind speeds for each studied station (upwards arrow denotes increasing trend and downwards arrow denotes decreasing trend)

For some stations, such as London, although the annual maximum value of seasonal extreme wind speeds had a trend, the most frequently occurring wind speed did not necessarily occur in that season. Consequently, the detected trend for seasonal extreme wind speeds is not found for annual maximum wind speed. A similar trend analysis was carried out for task A5, in which the threshold wind speed of 55 km/h was selected for reasons stated previously. To simplify the analysis, this study categorized the wind speed data into 8 wind angle bins. Each angle bin has a 45-degree range. To illustrate the frequency of wind speeds occurred in each wind angle bin, the calculated frequency for each station is plotted in Figure 4. It can be observed that the local wind climate is very diverse for these 20 studied stations. Some of the stations, such as Iqaluit and Regina, have only a few dominant wind angles where wind would most likely come from. Other stations may have more probable wind angles, e.g., Shearwater, Saskatoon and Waterloo. It should be noted that the wind rose of normal wind speeds does not necessarily indicate the dominant wind angle of the annual maximum wind speed. For example, Figure 3 shows that the most frequent wind direction for Vancouver is east, but, the dominant wind angle for annual maximum wind speeds is northwest (i.e., facing to the Strait of Georgia). The purpose of examining these frequency plots is to understand the relative frequency of the wind direction, which can be used to carry out wind directionality analysis in structural wind engineering design. While leaving any probable change/trend of relative frequency of wind directionality out of scope of this study, the extreme wind speeds in each wind angle bin are analyzed. The detected trends are given in Figure 4 by using the arrows with same meaning as those in Figure 3. Besides some similar observations as those indicated in Figure 3, some interesting findings can be also seen in Figure 4. From the above analysis, an increasing trend is detected for Iqaluit. Figure 4 indicates that this increasing trend is caused by wind from North to East, where the station faces the sea. In other words, it may indicate that during winter time, the storm which causes wind coming from around northeast may become more active and frequent. Such deduction needs further study from a point of view of a large scale macro-meteorology.

4 REMARKS AND DISCUSSION

This study uses ground observations of wind speeds at meteorology stations at various cities across Canada to carry out trend analyses. Both annual maximum wind speeds and occurrence rate of wind speeds exceeding 55 km/h are studied. T-test and Mann-Kendall trend analyses are used to detect possible trend of extreme wind speeds. It is found that for annual maximum wind speeds from mixed wind climates, there are eight of twenty stations that have a statistically significant trend. The detected trends are decreasing for six stations, while two stations are indicated having an increasing trend. Similar trends can be detected if the thunderstorm wind speeds are filtered out. However, trends were seldom detected in thunderstorm annual maximum wind speeds, or in annual occurrence rates of thunderstorms. There were three stations, including Shearwater, Quebec City and Sudbury that showed a decreasing trend of thunderstorm annul maximum wind speeds. Similar trend analyses are carried out for annual maximum values of seasonal extreme wind speeds and directional wind speeds. The results indicate that the trends detected for some stations mainly occurred in one or two seasons, those in which the wind speeds are most frequently occurring. For some other stations, there was no trend detected from the seasonal analysis, which indicates that the change of the wind speeds may be distributed more randomly among seasons. Results from the directional trend analysis indicate the possible wind direction where the extreme wind speeds having a trend. Such findings can be used for further study on the causes of that trend.

It is important to note that although changing trends in maximum wind speeds over time have been identified, this does not constitute evidence that these trends are directly caused by climate change, only that it is a possible indication. While reasonable efforts have been made to ensure that the data have been homogenized with respect to height and exposure, the influences from changes in instrumentation and exposure are much more complex than can be addressed through simplified adjustments. As such, there is still a degree of uncertainty in end results. In addition, there could be other larger scale influences that may produce impacts on climate over a longer period (e.g., inter-annual variations like El Niño\La Niña and inter-decadal variations like Pacific decadal oscillations) that have not been considered here. Some of these issues may have influenced some of the regional discontinuities of the detected trends that can be observed in this study. For example, the extreme wind speed for Vancouver international airport is detected as having an increasing trend. However, a station in the close area at Victoria international airport has no statistically significant trend. In terms of the directional extreme wind speeds, there is an increasing trend detected for both Vancouver and Victoria, but not for exactly the same wind directions. The physical mechanism causing this phenomenon is not clear yet. To better appreciate localized trends, research on the uncertainties of the trend analysis and regional trend analysis need to be carried out in future studies.

The final purpose of the trend analysis was to set up the basis for future studies of the impact of trends on the estimation of design wind speeds. For stations with a decreasing trend in annual maximum wind speeds, there might be no urgent action needed as a linear non-stationary probabilistic model will lead to a lower design wind speed. For those stations having an increasing trend, the estimated design wind speeds will be increased by using the non-stationary probabilistic model. The impact of such trends highly depends on the extent of the detected trends and the non-stationary model used. For example, one may simply use a linear non-stationary function to model the Gumbel distribution parameters. The detected trends in this study are mostly decreasing, while the trends in future scenarios found in some publications by using numerical forecast models are increasing. Therefore, before applying any non-stationary probabilistic model, further studies are needed to identify the causes of these differences.

Acknowledgements

The present studies were partly funded by RWDI and partly through funding provided by the National Research Council of Canada. The authors thank Mr. Juan Park for assisting with data processing.

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